OSpace: Towards a Systematic Exploration of Olfactory Interaction Spaces

Dmitrijs Dmitrenko, Emanuela Maggioni, Marianna Obrist
SCHI Lab, Creative Technology Research Group, School of Engineering and Informatics
University of Sussex, Chichester I, Falmer, Brighton, BN1 9QJ, UK
{d.dmitrenko, e.maggioni, m.obrist}@sussex.ac.uk

ABSTRACT
When designing olfactory interfaces, HCI researchers and practitioners have to carefully consider a number of issues related to the scent delivery, detection, and lingering. These are just a few of the problems to deal with. We present OSpace - an approach for designing, building, and exploring an olfactory interaction space. Our paper is the first to explore in detail not only the scent-delivery parameters but also the air extraction issues. We conducted a user study to demonstrate how the scent detection/lingering times can be acquired under different air extraction conditions, and how the impact of scent type, dilution, and intensity can be investigated. Results show that with our setup, the scents can be perceived by the user within ten seconds and it takes less than nine seconds for the scents to disappear, both when the extraction is on and off. We discuss the practical application of these results for HCI.

Author Keywords
Olfaction; Smell; Odour Stimulation; Olfactory Interaction Space; Scent-Delivery; Multimodal Interfaces.

ACM Classification Keywords
H.5.m Information interfaces and presentation (e.g., HCI); H.1.2 User/Machine Systems: Human factor.

INTRODUCTION
The field of olfactory interaction has fascinated researchers and engineers for over a century, however, only recently it gained new momentum through advances in our understanding of the human olfactory system [11, 8], insights into olfactory experiences [28], approaches to digital smell interfaces [30], and the design of scent-delivery devices [9]. While guidelines for audio-visual, and increasingly for haptic [10, 32] interaction design have been established, olfaction often leaves designers clueless about what scent-delivery approach to use, how to build a delivery device, how to equip an interaction space and to configure the equipment. Without guidance on those questions, we don't know if the olfactory interface is designed appropriately for the intended use.

ISS '17, October 17–20, 2017, Brighton, United Kingdom

ACM ISBN 978-1-4503-4691-7/17/10…$15.00
https://doi.org/10.1145/3132272.3134121

Recent proposals on the design of an olfactory interaction space include a vortex based scent-delivery setup [36], an exhibition booth enhanced by smell [3], an artwork with an interactive olfactory interface [19], and a room with "dynamic olfactory zones" [13]. Moreover, there is a variety of scent-delivery devices that have been built as one-off applications for gaming [24, 17, 1], ambient notifications [5, 35], simulated driving [12, 37], and virtual reality [23, 7]. Nevertheless, all of these research activities are linked to specific applications, the scent-delivery parameters (e.g. distance, intensity, delivery time) are ad hoc, and the scent cross-contamination and lingering issues are often addressed as limitations without rigorous solutions.

We synthesised insights from prior research and determined specific design parameters for a scent-delivery device and an olfactory interaction space. In summary, the contributions of our paper are:

i. A novel setup enabling scent detection time of 10s and scent lingering time of <9s for the distance of 68cm from the device output to the user's nose.

ii. A scent-delivery device allowing the control of the type and dilution of scents, as well as the air pressure these scents can be delivered with, and also the delivery time.

iii. A detailed exploration of scent-delivery and air extraction parameters in the scope of olfactory interaction spaces supported by a user study.

iv. A non-invasive air extraction method for desktop olfactory interaction applications.

v. A novel set of recommendations (i.e. OSpace) to design and build a scent-delivery device and an olfactory interaction room.

vi. Practical application suggestions of OSpace in HCI.

Based on the research presented in this paper, we now know that OSpace can help to define all the parameters addressed above (in relation to the intended setup) and to create a well-controlled environment for studies on olfactory interaction.

RELATED WORK
Here we review prior related work on olfactory interaction, covering scent-delivery device proposals and their applications, explorations of scent-delivery parameters, and the design of olfactory spaces.

Scent-Delivery Devices

There are a number of commercially available scent-delivery devices that HCI researchers have access to today [9]. Multiple examples of their successful integration into interactive olfactory systems have been presented. For example, Brewster et al. [6] demonstrated the use of a smell-based photo tagging tool in their Olfoto prototype, while Bodnar et. al. [5] and Warnock et al. [35] studied the use of smell as an ambient notification modality. Nevertheless, the capabilities of such devices (e.g. choice of scents, delivery distance, and resistance against cross-contamination) are rather limited, which also restricts the range of their applications. Moreover, those devices are often expensive [18, 14], which motivated many researchers to design and build their own prototypes.

Lundström et al. [20] proposed a very good ”do-it-yourself” approach of building an inexpensive scent-delivery device, which is excellent for temporally-precise olfactory studies, but has little applicability in HCI due to the requirement of wearing a nosepiece (a very invasive interface). Moreover, Herrera and McMahan [14] proposed a method to build a simple and inexpensive scent-delivery device that could be easily applied for VR studies and other immersive applications. However, this prototype only contains one scent. McGookin and Escobar [22] pushed this idea further and came up with an approach for creating an open-source scent-delivery device that contains multiple scent cartridges. The benefit of their solution is not only a proposal of a reliable, cheap, easy-to-build mechanism but also a suggestion of using this device in a broad range of use cases, including both static (e.g. desktop) and mobile applications. However, no user studies have supported these claims and hence only provide limited guidance beyond this one-off implementation.

There is a number of prototypes capable of delivering multiple scents, the efficiency of which has been demonstrated in practice. Ando [3, 2] presented a device allowing to rapidly switch between multiple scents. By containing six different scent cartridges very close to each other, he was able to instantly redirect the flow of the compressed air from one cartridge to another. However, he did not explain how to eliminate the cross-contamination problem inside the device. Nakamoto et al. [24] proposed a mechanism with clearly separated scent channels. The advantage of their setup was the option of choosing which scents the user wants to mix. This function was demonstrated through a cooking game. Due to individual scent channels, the mixing process could be easily controlled and was going on without unwanted contamination. Although this prior work tackles one challenge in olfactory interaction, it does not provide insights into how far the scent can travel and what the constraints are in terms of scent lingering artefacts.

Another example of smell enhanced gaming was proposed by Abid et al. [1], who built a heat based scent-delivery device and presented it in an immersive 3D shooter game, where the users could smell several kinds of smoke. This is a very original approach, but due to the application of the laser, which is burning solid odorants, the extendibility of this use case to further scenarios is limited.

When it comes to wearable devices, their applications can be found in the fields of augmented and virtual reality. Narumi et al. [25] created a MetaCookie prototype for gustatory applications enhanced by smell, which gave the users an opportunity to taste different flavours from a regular sugar cookie by just changing the scents emitted during the interaction process. Covarrubias et al. [7] have proposed a system to apply scents as a reward stimulus in rehabilitation exercises. Both Narumi et al. and Covarrubias et al. have suggested attaching the output of the scent-delivery device to the VR/AR headset, while Mochizuki et al. [23] came up with an idea of placing it on the users' hand to help them explore the scents of the virtual objects they are grasping. Despite many technical details related to the functionality of the entire system presented in these papers, we still know very little about how to decide what scent dilution level shall we use for wearable devices, how far from user's nose do we need to place the output, what air pressure shall we choose, etc.

Taken together, the olfactory design space gained lots of attention but is diverse and scattered in its approaches. Below we review in more detail specific scent-delivery parameters.

Parameters for Scent-Delivery

Yanagida et al. [36], for instance, explored different interaction distances using an ”air cannon” approach. While this underlines the relevance of the delivery distance as a design parameter in olfactory stimulation, the authors did not provide any justification for setting it to 120cm. Abid et al. [1] proposed placing the output 70cm away from the participant for their heat-based scent-delivery prototype, but also did not explain the pretests conducted to identify it.

As well as the distance, the scent dilution is a relevant design parameter and can influence choices with respect to the intensity and frequency of olfactory stimulation. Seigneuric et al. [33] studied crossmodal associations between olfaction and vision using twelve different scents (apricot, bacon, banana, coffee, strawberry, melon, orange, fish, lavender, rose, soap, and vanilla) with different dilutions. While the variety of explored scents is impressive, the rationale behind the choice of the dilution levels is not transparent.

Another parameter to consider is the timing of the scent-delivery. Noguchi et al. [26] proposed pulse ejection of a scent in six timings (0s, 0.2s, 0.4s, 0.6s, 0.9s, and 1.3s) after the beginning of the moment of breathing in. This approach requires precise detection of the moment when the user inhales. Moreover, the scent-delivery distance studied here (10cm) is rather short compared to the majority of mid-air applications. Also, it is not clear, how the timings change depending on the scent. In another proposal, Yoshida et al. [37] discovered the alerting and awakening effect of scent when presented at 30s intervals, but the specifics of the interval design in relation to the scent dilution (e.g. can the interval be reduced with higher scent dilution) remain unclear.

Various prior studies have investigated the use of pressurised air with limited insights on the pressure values or their selection [3, 20, 37]. For example, Lundström et al. [20] used a compressor capable of maintaining the pressure of 2 bars, while Yoshida et al. [37] applied a compressor without mentioning what pressure it was set to. Ando et al. [3] have used an air-blower which was creating a pressure inside a cube located on top of it. A small opening on top of the cube helped to create an airflow, which would transmit the scent to the user's nose. No pressure levels are known from this approach either. Nevertheless, the pressure values are very important as they affect scent intensity.

Finally, there also seems to be no standard of how to approach the problem of scent lingering in a room after the delivery. Brewster et al. [6] reported having conducted an experiment in a "well-ventilated room", but Bodnar et al. [5] said they "limited the amount of scent", without mentioning the details. Lai [19] made use of the building's centralised ventilation system, acknowledging that an individual ventilation system would have been a better solution.

Today, researchers seem to be using their best guess for the ventilation problem, but we remain uninformed about their actual effect on the olfactory stimulation and perception, which is particularly relevant when exploring olfactory interfaces in enclosed spaces (e.g. virtual environments, desktop gaming, multimedia, in-car interaction).

Olfactory Interaction Spaces

Multiple researchers have tackled the problem of designing for olfactory interaction in physical spaces, areas such as museums and exhibition halls, or for the automotive context.

An olfactory interaction setup without a strict application context was proposed by Yanagida et al. [36], whose device allowed multiple users seated only 50cm away from each other to receive their own stimuli from the same "air cannon". This was possible due to the vortex ring technology and a very small amount of scent being injected into the vortex.

In the context of exhibition and museum rooms, Ando et al. [3] have proposed a setup in which visitors were interacting with virtual representations of antique objects being able to not only touch but also smell them by means of a scent-delivery device equipped with a piezoelectric blower. Moreover, Lai [19] presented a museum room in which scent-delivery devices motivated the users to explore a piece of modern art. Finally, Haque [13] described an olfactory interaction space based on "dynamic olfactory zones and boundaries" floating through the room and engaging visitors to interact with different scents.

In the automotive context, Funato et al. [12], and Yoshida et al. [37] presented complete solutions of an olfactory interaction space in the context of simulated driving. Funato et al. used the "air cannon" to deliver the scent to the driver, while Yoshida et al. applied scent chambers connected to an air compressor. Both of these research activities have targeted the problem of keeping drowsy drivers awake by means of awakening scents.

Even though these are some good examples of how to build an olfactory interaction space, multiple issues (e.g. scent-delivery time, room ventilation) are not very well discussed. This lack of a standardised framework of olfactory interaction is slowing down the advancements in this field, not allowing researchers to verify the methods applied in all the different techniques. We are making a first step towards filling this gap and propose a step-by-step approach to designing, building, and exploring an interactive olfactory environment.

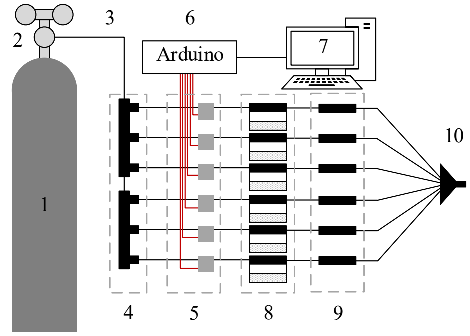


Figure 1. Structure of the scent-delivery device: 1 - air tank, 2 - manometer, 3 - plastic tube, 4 - two manifolds, 5 - six electric valves, 6 - Arduino board, 7 - PC, 8 - six jars containing the scents, 9 - six one-way valves, 10 - output nozzle.

DESIGNING AN OSPACE

We demonstrate how the parameters of this setup can be carefully investigated to understand the ways of the meaningful application of the OSpace in HCI.

Scent-Delivery Device

Based on the problems encountered in the commercially available scent-delivery devices [9] and the knowledge collected from multiple existing scent-delivery prototypes (e.g. [20, 36, 26, 24]), we extracted the following device characteristics:

i. scent blowing distance of $\geq$50cm (to allow some space for hand movements, like in [36, 1]).

ii. well isolated channels for each scent (as per [20, 24]).

iii. control of the blowing time and scent intensity [3, 2].

iv. delivery of multiple scents to the user in a single session and replacement of the scents between the sessions [20, 2].

v. option of rapidly switching between the presented scents (the timing of which we decided to explore in our experiment since insufficient information on this is available).

To comply with the distance requirement, we decided to adapt the approaches of Yoshida et al. [37] and Ando et al. [3, 2]. Both of them used pressurised air to deliver a scent to the user. To ensure a satisfactory level of air pressure (up to 1.5 bars [20]), and to comply with health and safety regulations, we discarded the idea of an air compressor, and installed an air tank (see Figure 1.1), which can be manually controlled by means of a manometer connected to it (see Figure 1.2).

To make sure we have separated and well-isolated channels for each scent, the clean and the saturated air are delivered through individual plastic tubes (4mm in diameter for the scents and 6mm for the compressed air source). The clean air

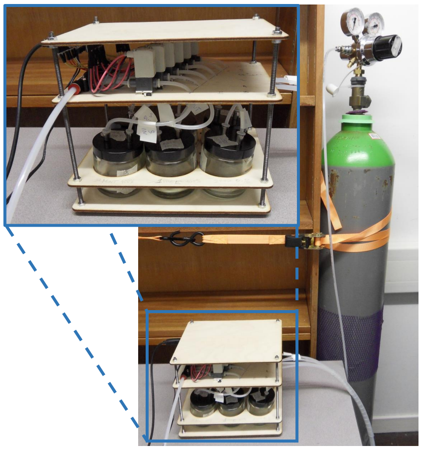


Figure 2. Scent-delivery device (20.5×16.5×22.5cm) with the air tank (150.0×25.0×25.0cm).

tube is connected to the air tank (see Figure 1.3). To split the clean air channel into six separate scent channels (one tube per scent), we used two Norgren Pneufit C C00D30604 manifold unions with two 6mm outlets and three 4mm branches each. Connecting them in the way depicted in Figure 1.4, we could create six well-isolated scent channels. Such a setup is scalable and can be easily extended towards further scent channels (e.g. adding just one more manifold would give another three channels).

To be able to control the blowing time, we let each scent channel go through an electric valve (see Figure 1.5). Each valve (SMC Compact Direct Operated 2 Port Solenoid Valve) was connected to an Arduino board (see Figure 1.6), which we controlled through our software (written in Java) running on a Windows PC (see Figure 1.7). Using Arduino and electric valves, we were able to rapidly (valve response time of ∼30ms) trigger the scents delivery, and to adjust its duration. By manually operating the manometer, we could control the air pressure (used to vary the scent intensity).

To enable the delivery of multiple scents to the user in a single session, we connected each of the six air channels to one of the six glass jars (see Figure 1.8), which are suitable for both liquid and solid scents. In our setup, we decided to explore liquid scents, because they are easy to obtain (in the form of essential oils) and straightforward to use for the first prototype. The glass jars (see Figure 2) do not absorb scents and can be closed tightly (using ethylene-vinyl acetate sealing) to avoid leakage. Jars (including their metal covers) can be easily washed (in hot water mixed with sodium bicarbonate) and filled with a new scent, when necessary. This ensures the requirement of replacing the scents between the sessions is met. Extensibility can be achieved by installing an additional layer of jars into the scent-delivery device (see Figure 2).

To eliminate uncontrolled flow of scents from the jars to the output of the device (see Figure 1.10), we directed each scent channel into a one-way valve (six Norgren T51P0004 4mm Inline Non-Return Valves, see Figure 1.9), which would let the air go through only above a certain pressure.

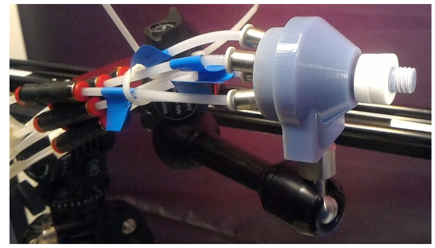


Figure 3. The 3D printed output nozzle of the scent-delivery device connecting all six scent channels into one output tube (20mm long), directing the airflow. The end of the nozzle is designed in the way that it can be easily connected to any ≤8mm thick plate with a hole of 9mm in diameter in it. It can also be mounted on a tripod.

Finally, all six scent channels are connected to the 3D printed output nozzle (see Figure 1.10). The nozzle collects six scent tubes together and has an extended end (20mm in length, see Figure 3), which helps to stabilise the airflow and direct it towards the user's nose.

Olfactory Interaction Room

If we decide to release scents into a room, we also need to make sure they disappear quickly, to avoid scent habituation, and to be able to release new scents without the problem of scent mixing. For this purpose, a dedicated room design and a setup are necessary to facilitate research of olfactory interaction. Based on consequences of using olfactory interfaces addressed in [6, 5, 19], we defined a set of requirements. The olfactory interaction room needs to be

i. composed out of materials that do not absorb scents.

ii. independent from the building's centralised ventilation system to enable direct control over the air in the room.

Here we define the specific setup and configurations for the olfactory interaction room we designed and built. We used a former softwall clean room construction (from Connect 2 Cleanrooms Ltd.). Due to the size of this room (H= 2.1m, W= 1.3m, L= 2m), it has the potential to be used for multiple applications (e.g. multisensory cinema for 1-2 users, gaming, driving simulator, or even VR use cases). In this paper, we present a setup that is purpose-made to explore the olfactory interaction parameters (see Figure 5), but it can be further extended to any of the applications listed above.

We have removed the clean room's original plastic walls (because of their intense smell) and exchanged them with the black odourless water-repellent fabric (made of polyester, not absorbing scents, see Figure 4).

We have equipped our olfactory interaction room with two air extractors (see Figure 5): E1 - Torin-Sifan DDC270-270 (550W, 50Hz, 69dB) extractor mounted on the ceiling of the room and E2 - Vent-Axia ACM200 B 17108010C (109W, 50Hz, 38dB) in-line extractor connected through a pipe to a ventilation grid in the surface of the table inside the olfactory room. With such a setup, we were not relying on the building's centralised ventilation system. To motivate installation of two air extractors, it is important to mention that we initially conducted a prestudy 1 with only the extractor E1. In

Figure 4. Olfactory interaction space: clean room wrapped into a black water repellent fabric with an air extractor E1 and the clean air blower on the top, as well as a scent-delivery device and an air extractor E2 in the bottom-left corner (outside the clean room).

prestudy 1, we carried out a between participants exploration with 23 subjects, with a mean age of 31 years (SD= 6.1 years, 8 females), where 12 participants measured the scent lingering time with the extraction off and 11 with the extraction on. The results of prestudy 1 showed no immediate impact of the extraction on the scent lingering time. We hypothesised that it might have been due to extractor E1 being located too far away from the scent-delivery output and decided to install an additional extractor E2, which would be much closer both to the output and to the participants' nose. Another issue that caused a lot of variability in the data collected in prestudy 1, were the head movements of the participants. For this reason, in the improved setup, we decided to install a chinrest, which would help us fix the position of the head and the nose and keep it constant across trials and subjects. Such an approach has already been applied in olfactory studies [26].

The clean room also came with a clean air blower (Envirco Corporation Mac 10 XL), which is equipped with a high-efficiency particulate air (HEPA) UL900 filter (99.99% efficient at 0.3 Micron), capable of filtering the odour molecules. We have left the exploration of this device for the future work.

The air tank and the scent-delivery device were located outside the olfactory room, and only the plastic tubes of six scent channels were going into the room (see Figure 5).

Positioning the Output of the Scent-Delivery Device

When deciding on the correct position of the scent-delivery output within the room, it is essential to make sure that

i. the output nozzle does not interfere with user's movements.

ii. the device is capable of sending the scent over the necessary distance from the nozzle to the user's nose

As we plan to investigate olfactory interaction in a driving simulator, we decided to locate the output nozzle just behind the steering wheel of a driving simulator device (possible occlusions would be prevented applying a distance sensor).

To identify the distance we will need to deal with in such a use case, we conducted a prestudy 2 with 15 participants, with a mean age of 32 years (SD= 5.2 years, 3 females). In prestudy 2, participants were instructed to adjust the seat of the driving simulator the way they feel comfortable to perform the driving task. When the position of the seat was fixed, we measured the distance from the nozzle to participants' face using the ultrasound distance sensor. The shortest distance recorded in prestudy 2 was 43cm, but the longest 63cm (M= 56cm, SD= 5.15cm). To make sure that our scent-delivery device works in this distance range, we took the distance of 68cm (MAX + SD) for our OSpace exploration study.

Summary

Following the OSpace recommendations, we have built an exemplary olfactory interaction space. The main component of our setup is the scent-delivery device capable of releasing different scents (with different dilution levels), for a customisable time, under various air pressure conditions. We created an olfactory interaction room composed of materials that do not absorb scents (metal, plastic, and water repellent fabric made of polyester). This room is equipped with two extraction fans to help remove the scents released by the device. To explore the scent-delivery and air extraction parameters of our olfactory interaction space, we have also installed a chinrest, which helps to keep the conditions consistent across trials and participants. We summarise all these components in Figure 5. In the next section, we present the study conducted to investigate the above-mentioned parameters. In particular, we focus on the scent detection and lingering time, as well as the hedonic perception of scents (liking, comfort, and intensity).

THE STUDY

In this section, we present the user study performed to explore the olfactory interaction space designed and built following the requirements set out in the OSpace design phase.

Study Design

We conducted a mixed model study, in which we explored three different air pressure levels (0.5, 1.0, and 1.5 bars [20]) as a between participants condition, but scents (lemon, peppermint, rose), dilution levels (100% pure essential oil, 50% dilution with water), and air extraction (on/off) as within participants conditions. The distance of the scent-delivery (from the output to the participants' nose) was constant: 68cm.

Our dependent variables were scent detection time (when do the participants start perceiving the scent after it has been released) and scent lingering time (when do they stop perceiving the released scent) recorded by a button press. Further dependent variables include the scent liking, comfort, and intensity values (self-report measurements, 7-Point Likert scale).

Choice and Presentation of Scents

The scents of lemon and peppermint have been employed in a number of olfactory studies [16, 4, 21, 31, 37], which supported our choice to apply them. Since both lemon and peppermint are highly arousing, we decided to also include one soothing scent - rose, which has been referred to as relaxing in the related work (see [15]). Other applications (e.g. multisensory cinema) might involve some other scents [34].

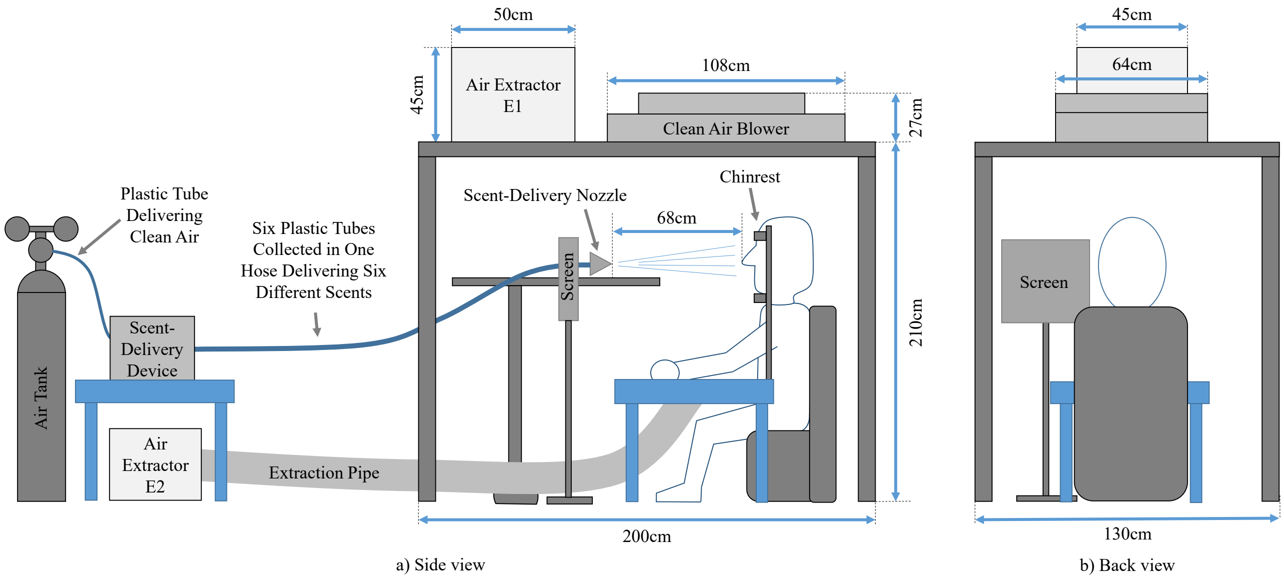


Figure 5. Side and back views of the olfactory interaction space with the scent-delivery device connected to an air tank, delivering a scent to the user seated inside the olfactory interaction room. User's head is fixed on a chinrest, and the delivered scent is extracted through a pipe connected under the table. The user is rating the investigated parameters by answering questions on the computer screen. There is an additional air extractor on the top of the room to refresh the air between the interaction sessions. A clean air blower can be applied to propel filtered air in from the outside (an option to explore in the future work).

For the user study, we filled each jar of our scent-delivery device with six grams of the corresponding 100% pure essential oil, or with three grams of the essential oil and three grams of water to create a 50% dilution of a scent. We used the *"miaroma"* 100% pure essential oils from Holland & Barrett International Limited and tap water for the dilutions.

Participants

A total of 21 participants, with a mean age of 32 years (SD= 7.8, 6 females) volunteered for this study. Participants have reported having no olfactory dysfunctions or adverse reactions to strong smells (e.g. migraines), not suffering from any respiratory problems (e.g. asthma), or from the flu, and not being pregnant. There were seven participants for each between-subjects condition mentioned previously. We have invited participants from different cultures. The countries the participants came from include France, Italy, Spain, Greece, Palestine, Uganda, Vietnam, Japan, Mexico, USA, and UK.

Procedure and Method

Upon arrival, participants were given the information sheet, an explanation of the procedure, and a consent form to sign (the procedure and method of this study were approved by the ethics committee of the University of Sussex).

We then asked the participants to take a seat on the chair inside the olfactory interaction room and to follow the instructions on the screen (17" screen, 60Hz refresh rate). They were instructed to interact with the graphical interface shown on the screen using a mouse (see Figure 6). During the experiment, participants wore headphones playing pink noise to cancel the sounds created by the scent-delivery and to avoid potential bias. Below we present different blocks of the study, which were separated by a break of 30s.

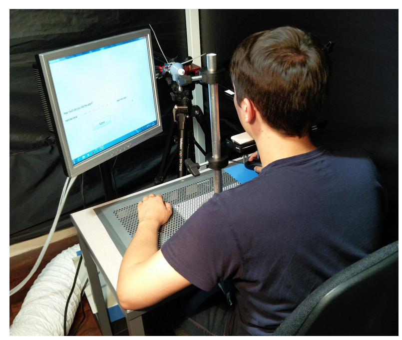


Figure 6. A participant inside the olfactory interaction space designed following the OSpace recommendations, to study the scent-delivery and air extraction parameters. During the study, the participants also wore noise-cancelling headphones (not depicted in this figure).

Scent Familiarisation Phase

The following message was shown on the screen at the beginning of this first step: *"Welcome to the experiment! In the first 6 trials, you will have a chance to familiarise yourself with all 6 scent stimuli we use in this experiment! Please place your head on the chinrest!"*. After the participant had clicked the *"OK, I'm ready!"* button, the following message appeared on the screen: *"Press 'Start', when you detect the scent!"* Scent delivery started five seconds after this message appeared on the screen. We delivered the scent to the participants for five seconds in each trial, which is a sufficient time frame to cover at least one in- and one exhalation (according to [29]). As soon as the participant clicked the *"Start"* button, a *"Press 'Stop', when you stop perceiving the scent!"* message appeared together with the *"Stop"* button. The following three questions were shown to the participant after the press of the

"Stop" button: *(1) "How much did you like the scent? (1= "Did not like it at all"; 7= "Liked it very much")"; (2) "How would you rate your comfort with this scent? (1= "Very uncomfortable"; 7= "Very comfortable")"; (3) "How would you rate the intensity of this scent? (1= "Not intense at all"; 7= "Very intense")"*.

Participants could answer these questions by clicking the corresponding value (1-7) on the scale and confirming their response by pressing the *"Submit"* button. The six trials of the familiarisation phase included stimulation by all three scents (lemon, peppermint, rose) with two dilutions levels (100% pure essential oil, 50% dilution with water) per each scent. The order of the scents and dilution levels were randomised across the participants based on the Latin square. Air extraction was off in this step of the study. Since the aim of this part was to help the participants compare the scents with each other for more objective scent liking, comfort, and intensity ratings in the remaining part of the study, we did not analyse the data collected in this phase.

Explicit Scent Detection and Lingering Time Measurements
In this step of the study, the participants were shown exactly the same instructions as in the familiarisation phase, but this time their button press activities and self-report data were recorded. Participants performed this step twice (once with extractor E2 on, and once with extractor E2 off). Both the order of the scents/dilutions and the air extraction conditions were randomised based on the Latin square. Just like in the previous step, scent delivery started with a five seconds delay after the instructions of each trial were displayed.

Implicit Scent Lingering Time Measurements
This step of the study started in a similar manner as the two described above, with the difference that clicking the *"Start"* button triggered the appearance of the following question: *"How would you rate the intensity of this scent right now? (1= "Not intense at all"; 7= "Very intense")"*. This question appeared on the screen every 10s (after 0, 10, 20, and 30s), replacing the *"Stop"* button and giving participants a chance to implicitly report the lingering time of the scent. There was a *"Please wait"* message shown between the intensity questionnaires. We introduced this step to help the participants realise when is the scent really not perceivable anymore.

From the participants' feedback collected in prestudy 1, we understood that it was not easy to understand when a scent is really gone because some intense scents were leaving an arousing feeling in the nose, despite not being present anymore. By sampling the lingering time in the chunks of 10s and asking to rate the scent intensity by the end of each chunk, we could see how the intensity drops over the time. Participants were instructed to give the score of 1, if they did not perceive the scent anymore. This step was also performed twice (once with extractor E2 on, and once with extractor E2 off). Both the order of the scents/dilutions and the air extraction conditions were randomised based on the Latin square.

We concluded the experiment with the demographic questionnaire asking the participants to specify their age, gender, and the country(ies) they grew up and lived in.

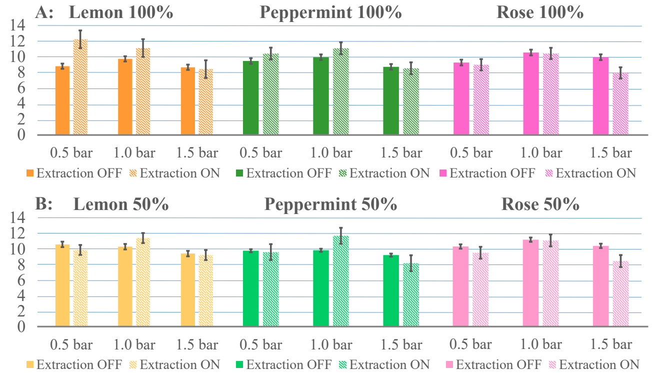


Figure 7. Mean Scent Detection times in seconds under the air pressure conditions of 0.5, 1.0, and 1.5 bars, for A: 100% pure essential oils of lemon, peppermint, and rose, and for B: 50% dilutions of lemon, peppermint, and rose essential oils with water. Error bars, ± s.e.m.

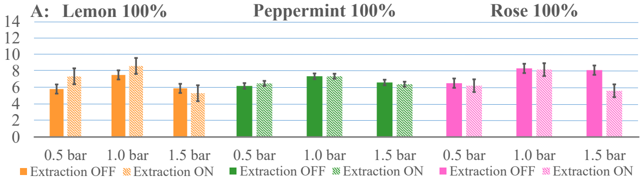
RESULTS
In this section, we present the results of our study: the observed scent detection/lingering times, air extraction issues, and hedonic scent perception (liking, comfort, and intensity).

We performed a normality test before applying parametric statistics [27]. A series of one-way-repeated measures ANOVA tests was performed to analyse the effect of the scent type (independent variable) on each of the dependent variables: scent detection and lingering times, as well as scent liking, comfort, and intensity. We report the results below.

Scent Detection and Lingering Times
The results show that any of the three observed scents (lemon, peppermint, rose), with two dilution levels each (100% pure essential oil and 50% dilution with water), can be perceived in no longer than 10s under any of the three air pressure levels (0.5, 1.0, 1,5 bars). These results are summarised in Figure 7. It also takes no longer than 9s for a scent to disappear in any of the observed conditions (Figure 8). From these two figures, we can also see that there are no significant differences across the detection (*$F(11, 198) = 1.10$, $p = .348$*) and lingering (*$F(11, 198) = 1.31$, $p = .168$*) times recorded under all the different combinations of the above mentioned conditions.

Air Extraction Effect
The results from our study demonstrate that the scent detection and lingering times do not change depending on the air extraction conditions (see Figures 7 and 8). The fact that there are no statistically significant differences in the scent detection (*$F(11, 198) = 1.10$, $p = .348$*) and lingering (*$F(11, 198) = 1.31$, $p = .168$*) times between the extraction on and off conditions proves the efficiency of our scent-delivery device. The results confirm that our device releases such a small amount of the scent that there is no need for an extraction system to work in parallel with it. In fact, in both cases, it is enough with 10s for the participant to detect any of the explored scents, and with 9s for this scent to disappear.

Hedonic Scent Perception
Further results indicate high mean ratings of the perceived liking (e.g. 5.7 for Lemon, 4.9 for Peppermint, and 5.7 for



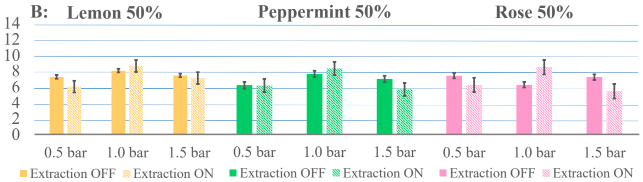


Figure 8. Mean Scent Lingering times in seconds under the air pressure conditions of 0.5, 1.0, and 1.5 bars, for A: 100% pure essential oils of lemon, peppermint, and rose, and for B: 50% dilutions of lemon, peppermint, and rose essential oils with water. Error bars, ± s.e.m.

Rose undiluted essential oils in the 1.0 bar condition, with air extraction off) and comfort (e.g. 5.1 for Lemon, 4.7 for Peppermint, and 5.7 for Rose undiluted essential oils in the 1.0 bar condition, with air extraction off), which suggests that all the explored scents have a big potential in HCI, since users would like them and feel comfortable about interacting with them. In addition to that, there is no need to worry that one scent would be liked less than the other one, or that a choice of the scent might decrease the comfort, since the differences between the perceived liking ($F(11, 198) = 1.16, p = .288$) and comfort ($F(11, 198) = 1.16, p = .292$) ratings are not statistically significant.

We recorded the increase of the perceived scent intensity with the change of the air pressure (e.g. the mean scores of 2.9 in the 0.5 bar and 4.6 in the 1.0 bar conditions of the rose essential oil diluted to 50% with water, when air extraction was off). Nevertheless, the differences in the perceived intensity ($F(11, 198) = .86, p = .652$) were not statistically significant. We discuss what it means and what impact it has on the future research in the coming two sections.

DISCUSSION

The scent detection and lingering times identified in this study are too slow for real-time applications (unless the target event can be predicted 10s in advance), but open multiple opportunities for feedback and feedforward messages (e.g. olfactory feedback on the objects the user is interacting with in gaming [24, 23] or VR [7, 25], warning feedforward messages in the autonomous driving scenarios). Another application example can be found in the scope of the multisensory cinema (e.g. like in [34]), where a scent accompanies a certain scene of the film, and transitions between the scenes are smooth enough to release a new scent.

As the results suggest, an HCI researcher or practitioner exploring olfactory interaction might not need to worry about the timing changes depending on the type of the scent or its dilution, when applying our setup. This is supported by the lack of statistically significant differences between the scent detection and lingering times. Nevertheless, this finding still needs to be confirmed by a study with a bigger sample size.

This might reduce the implementation effort and exclude a chance of setting a wrong delivery time of a specific scent or a wrong time-out after it has been delivered. These values could be kept consistent across the stimuli, which would be relevant e.g. for gaming applications [24, 1], or in-car olfactory interfaces [12, 37], where multiple scents are used.

Our results on the air extraction effect, contribute a lot to solving the issues, which so far have been only referred to as a limitation in HCI (e.g. [5, 6, 35, 19]). Our exploration of the air extraction parameters, in relation to the automated scent-delivery, suggests which extraction requirements we need to fulfil for our setup. We hope that other HCI researchers can apply the same strategy for their olfactory interfaces.

The extractor E2 might well be useful for ambient desktop notification systems like [6, 5], but extractor E1 for ambient scenarios on an even larger scale, where there is a need to saturate the entire olfactory room with a scent, e.g. in user behaviour studies under the effect of an ambient scent (like in [4]). Both of these extractors did not demonstrate an effect in this study and the prestudy 1 we conducted earlier, which demonstrates that no extractors were needed for these scenarios and suggests their necessity in other applications.

An olfactory HCI designer might still stay confused about what air pressure to use since it seems to have no impact both on the scent detection speed and the lingering time. Even though the ratings of comfort and liking of each scent are not significantly different, a good suggestion would be to take a look at these ratings for each of the scents necessary for the desired application and to choose the pressure level based on the highest liking/comfort value. The choice could be made depending on what is more important for the intended use case (e.g. comfort might be more important for a multisensory cinema or driving, but liking for gaming or notifications).

To sum up, we can see that our results are promising and create a lot of room for new interaction potentials in HCI.

CHALLENGES AND FUTURE WORK

When working with the sense of smell, it is always necessary to acknowledge the challenges. Here we summarise the objectives we will need to further explore in the future.

As an outcome of prestudy 1, we found that extractor E1 had no impact on scent lingering. For this reason, we decided not to use it in the actual study, but we still ran it to refresh the air in the olfactory room between the sessions (when the room was empty). Another challenge of both air extractors installed in our setup was the noise. Even after placing the extractor E2 in a plastic box and covering the inner walls of the box with noise-cancelling materials, one could still hear the extractor running. Since the participants wore headphones, this had no impact on the results of the current study, but it would create an issue for use cases with a ”no headphones” requirement.

It is important to acknowledge that so far we have only studied an effect of air extraction (taking contaminated air out of the room through the window) in the exploration of the ventilation issues, even though ventilation also involves blowing fresh air in. In our case, we relied on the fresh air flowing in naturally when air inside the interaction space is extracted. In the future, we might explore the use of the clean air blower (see Figure 5), which can be especially useful when there is no access to the fresh air source (e.g. window), as often happens in exhibition booths. The impact of designing such a system in a larger or smaller room still needs to be investigated, however, we do not expect the results to change significantly, if the scent-delivery distance and the locations of the air extractors are the same as in our proposal.

The lack of statistically significant differences in the perceived scent intensity between the different air pressure levels is also understandable. It means that the intensity changes are not perceivable when triggered between subjects, motivating the need of a within subjects solution. Our current setup did not support changing the air pressure within subjects. In the future, we plan to solve this issue with a digital air pressure regulator and are sure that the changes of the intensity will be perceivable when performed within a single session.

The fact that all the recorded mean liking and comfort ratings were equally high (e.g. liking ratings of 5.7 for Lemon, 4.9 for Peppermint, and 5.7 for Rose undiluted essential oils in the 1.0 bar condition, with air extraction off) resulted in no statistically significant differences between them as well. This is not surprising though, since we were only using pleasant scents, which people like to sniff and apply to increase the comfort of their daily life (e.g. through deodorants, air refresheners). These results might change in the future studies, if we decide to investigate the effect of unpleasant scents.

In the current study, we have only investigated the interaction at the maximum distance (68cm) necessary for the target application (olfaction-enhanced driving), but in the future we would also explore other distances (e.g. the minimum, or the mean), to see how the perception changes there, and how the scent-delivery parameters should be changed depending on whether the distance grows or decreases.

Finally, it is worth acknowledging that our current setup is not portable. We are now assembling a mobile solution of our olfactory interaction system equipped with a transportable air compressor (Bambi PT24: Maximum Pressure - 8 bar, Noise - 54dB(A), Weight - 25kg, Size - 57×40×40cm), the air flow generated by which is suitable for inhalation. This would also eliminate the need to constantly check the air pressure inside the tank and refill it when it becomes empty.

CONCLUSION

Our findings show that with our setup, a scent can be perceived by the user in 10s and it takes less than 9s for the scents to disappear. Our user study confirms that such a performance is maintained also when the air in front of the user is not being extracted, proving that our scent-delivery device can also be applied without additional air extraction solutions. Our OSpace framework presents a novel set of recommendations (addressed in the "Designing an OSpace" section) for olfactory interaction design and creates multiple opportunities for the exploration of olfactory applications in HCI (such as in gaming, multisensory cinema, VR, and simulated driving). Our innovative concept makes the first steps beyond the one-off applications and creates a more generalizable and scientifically valid and rigorous approach for designing, building, and exploring the olfactory interaction spaces. It takes into consideration not only the usefulness of smell for a particular interaction scenario but also suggests ways to understand the details of how the scents can be delivered to the user, including the timing, scent type and dilution level, air pressure values, and air extraction requirements.

ACKNOWLEDGMENTS

The authors thank Jose Luis Berna Moya, Damien Ablart, Robert Cobden, Yutaka Tokuda, and Anna Konstantinova for their help on various stages of this project.

European Research Council
Established by the European Commission

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 638605 and No 737576.

REFERENCES

1. Abid, S., Li, Z., Li, R., and Waleed, J. Heat based odors delivery apparatus for interactive game playing. *International Journal of Multimedia and Ubiquitous Engineering* (2015).
2. Ando, H. Development of an olfactory display system capable of instant switching between aromas. *New Breeze* (2013).
3. Ando, H., Liu, J., and Kim, D. Multi-sensory interaction technology and its system application. *Journal of the National Institute of Information and Communications Technology* (2010).
4. Baron, R., and Kalsher, M. Effects of a pleasant ambient fragrance on simulated driving performance: The sweet smell of... safety? *Env. and Beh. 30*, 4 (1998).
5. Bodnar, A., Corbett, R., and Nekrasovski, D. Aroma: Ambient awareness through olfaction in a messaging application. In *ICMI '04*, ACM (New York, NY, USA, 2004).
6. Brewster, S., McGookin, D., and Miller, C. Olfoto: Designing a smell-based interaction. In *CHI '06*, ACM (New York, NY, USA, 2006).
7. Covarrubias, M., Bordegoni, M., Rosini, M., Guanziroli, E., Cugini, U., and Molteni, F. Vr system for rehabilitation based on hand gestural and olfactory interaction. In *VRST '15*, ACM (New York, NY, USA, 2015).
8. Dennis, C. Neuroscience: The sweet smell of success. *Nature 428*, 6981 (2004).
9. Dmitrenko, D., Vi, C., and Obrist, M. A comparison of scent-delivery devices and their meaningful use for in-car olfactory interaction. In *Automotive'UI 16*, ACM (New York, NY, USA, 2016).
10. Enriquez, M., MacLean, K., and Chita, C. Haptic phonemes: basic building blocks of haptic communication. In *Proceedings of the 8th international conference on Multimodal interfaces*, ACM (2006).

11. Firestein, S. How the olfactory system makes sense of scents. *Nature 413*, 6852 (Sept. 2001).

12. Funato, H., Yoshikawa, M., Kawasumi, M., Yamamoto, S., Yamada, M., and Yanagida, Y. Stimulation effects provided to drivers by fragrance presentation considering olfactory adaptation. In *Intelligent Vehicles Symposium 2009*, IEEE (2009).

13. Haque, U. Scents of space: an interactive smell system. In *ACM SIGGRAPH 2004 Sketches*, ACM (2004).

14. Herrera, N., and McMahan, R. Development of a simple and low-cost olfactory display for immersive media experiences. In *ImmersiveMe'14*, ACM (2014).

15. Hongratanaworakit, T. Relaxing effect of rose oil on humans. *Natural Product Communications* (2008).

16. Ilmberger, J., Heuberger, E., Mahrhofer, C., Dessovic, H., Kowarik, D., and Buchbauer, G. The influence of essential oils on human attention. i: Alertness. *Chemical Senses 26*, 3 (2001).

17. Ishibashi, Y., Hoshino, S., Zeng, Q., Fukushima, N., and Sugawara, S. Qoe assessment of fairness between players in networked game with olfaction. In *Proceedings of the 11th Annual Workshop on Network and Systems Support for Games*, IEEE Press (2012).

18. Kaye, J. Making scents: aromatic output for hci. *interactions 11*, 1 (2004).

19. Lai, M. Universal scent blackbox: Engaging visitors communication through creating olfactory experience at art museum. In *Proceedings of the 33rd Annual International Conference on the Design of Communication*, SIGDOC '15, ACM (New York, NY, USA, 2015).

20. Lundström, J., Gordon, A., Alden, E., Boesveldt, S., and Albrecht, J. Methods for building an inexpensive computer-controlled olfactometer for temporally-precise experiments. *International Journal of Psychophysiology 78*, 2 (Nov. 2010).

21. Martin, G., and Cooper, J. Adding zest to difficult journeys: Odour effects on simulated driving performance. In *The British Psychological Society Annual Conference* (2007).

22. McGookin, D., and Escobar, D. Hajukone: Developing an open source olfactory device. In *CHI EA '16*, ACM (New York, NY, USA, 2016).

23. Mochizuki, A., Amada, T., Sawa, S., Takeda, T., Motoyashiki, S., Kohyama, K., Imura, M., and Chihara, K. Fragra: a visual-olfactory vr game. In *ACM SIGGRAPH 2004 Sketches*, ACM (2004).

24. Nakamoto, T., Otaguro, S., Kinoshita, M., Nagahama, M., Ohinishi, K., and Ishida, T. Cooking up an interactive olfactory game display. *IEEE Computer Graphics and Applications 28*, 1 (2008).

25. Narumi, T., Nishizaka, S., Kajinami, T., Tanikawa, T., and Hirose, M. Augmented reality flavors: Gustatory display based on edible marker and cross-modal interaction. In *CHI '11*, ACM (New York, NY, USA, 2011).

26. Noguchi, D., Sugimoto, S., Bannai, Y., and Okada, K. Time characteristics of olfaction in a single breath. In *CHI '11*, ACM (New York, NY, USA, 2011).

27. Norman, G. Likert scales, levels of measurement and the laws of statistics. *Advances in health sciences education 15*, 5 (2010).

28. Obrist, M., Tuch, A., and Hornbaek, K. Opportunities for odor: Experiences with smell and implications for technology. In *CHI '14*, ACM (New York, NY, USA, 2014).

29. Ohtsu, K., Sato, J., Bannai, Y., and Okada, K. Scent presentation technique of pulse ejection synchronized with breathing. In *Ninth Annual International Symposium on Applications and the Internet, 2009. SAINT '09* (July 2009).

30. Ranasinghe, N., Karunanayaka, K., Cheok, A., Fernando, O., Nii, H., and Gopalakrishnakone, P. Digital taste and smell communication. In *Proceedings of the 6th international conference on body area networks*, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering) (2011).

31. Raudenbush, B., Grayhem, R., Sears, T., and Wilson, I. Effects of peppermint and cinnamon odor administration on simulated driving alertness, mood and workload. *North American J. of Psychology* (2009).

32. Schneider, O. *Haptic experience design: tools, techniques, and process*. PhD thesis, University of British Columbia, 2017.

33. Seigneuric, A., Durand, K., Jiang, T., Baudouin, J.-Y., and Schaal, B. The nose tells it to the eyes: Crossmodal associations between olfaction and vision. *Perception 39*, 11 (2010).

34. Suzuki, R., Homma, S., Matsuura, E., and Okada, K.-i. System for presenting and creating smell effects to video. In *ICMI '14*, ACM (New York, NY, USA, 2014).

35. Warnock, D., McGee-Lennon, M., and Brewster, S. Multiple notification modalities and older users. In *CHI '13*, ACM (New York, NY, USA, 2013).

36. Yanagida, Y., Kawato, S., Noma, H., Tomono, A., and Tesutani, N. Projection based olfactory display with nose tracking. In *Virtual Reality, Proceedings. IEEE* (March 2004).

37. Yoshida, M., Kato, C., Kakamu, Y., Kawasumi, M., Yamasaki, H., Yamamoto, S., Nakano, T., and Yamada, M. Study on stimulation effects for driver based on fragrance presentation. In *MVA2011 IAPR Conference on Machine Vision Applications* (2011).